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WAVEGUIDE ON OPTICAL THIN FILM LOSSES
I. THEORETICAL ANALYSIS

by

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EFFECT OF PROPAGATION ATTENUATION OF THIN FILM WAVEGUIDE ON OPTICAL THIN FILM LOSSES. I. THEORETICAL ANALYSIS

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Abstract: Theoretical analysis of three fundamental deficiencies of optical thin films is studied: the effect of the extinction coefficient of the refractive index, surface roughness effects, and refractive index nonuniformity on the propagation attenuation of thin film waveguides. Based on different deficiencies in the propagation attenuation of different guide modes in optical thin films, the article presents a method of distinguishing absorption and scattering losses in thin films.

Key words: optical loss, thin film, waveguide, light scattering, light absorption.

I. Introduction

Many researchers in China and abroad are intensely researching thin film losses and have proposed many methods, such as the photometric method [1], heat measurement method [2], and methods of measuring scattered light with space distribution [3]. In traditional methods, however, the detection light beam illuminates thin film specimens from the outside; the film thickness restricts the action distance of the detecting light beam into the thin film medium. Thus, test sensitivity of the traditional method is limited. In contrast to the traditional approach, propagation of waveguide light in thin films expands the action distance of light into the thin film medium. The propagation properties of the waveguide can sufficiently indicate the structural form of the thin film medium, thus enhancing the test sensitivity of thin film losses. However, because of the complexity of waveguide propagation in a thin film, analysis becomes very complicated with respect to the losses. The purpose of this paper is to discuss the analysis of thin film absorption and scattering losses due to waveguide propagation attenuation.

II. Theoretical Analysis

Consider a single-layer thin film system: n_s is the refractive index of its base, its surface is a medium with traces of roughness (marking as: $f_s(z)=x+d$); the thin film has a high refractive index n_f; its surface is a medium with traces of

roughness (marked as: $f_c(z)=x$) with k_f as the coefficient of light extinction for the surface; the refractive index of the thin film fluctuates randomly (marked as DELTA$n_f(z)$) along the z-direction, as shown in Fig. 1.

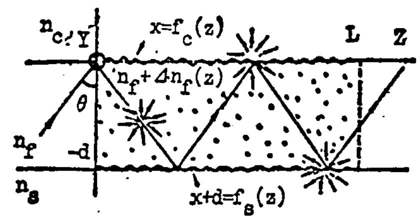

Fig. 1. Scheme of a single-layer optical thin film waveguide

Let us assume that the ratio between the roughness of two micro-rough boundary surfaces, the waveguide optical wavelength, and the thin film thickness are much smaller than 1; the random fluctuation amount DELTA$n_f(z)$ of the refractive index is also much smaller than the thin film refractive index n_f. In other words, DELTA$n_f(z) << n_f$; moreover, these deficiencies are random functions of the variable z, with the following statistical properties [4]:

$$\left.\begin{aligned} \langle f_c(z_1)f_c(z_2)\rangle &= \sigma_c \exp\left[-\frac{|z_1-z_2|}{l_c}\right], \\ \langle f_s(z_1)f_s(z_2)\rangle &= \sigma_s \exp\left[-\frac{|z_1-z_2|}{l_s}\right], \\ \langle(\Delta n_f z_1)\,\Delta n_f(z_2)\rangle &= \sigma_n \exp\left[-\frac{|z_1-z_2|}{l_n}\right]. \end{aligned}\right\} \quad (1)$$

In the equation, < > denotes the ensemble mean of the deficiencies along the z-direction; sigma$_c$ and sigma$_s$ denote the root-mean-square roughness of the corresponding boundaries;

$sigm_{an}$ is the root-mean-square of the refractive index fluctuation of the thin film; l_c, l_s, and l_n represent, respectively, the lengths of the corresponding deficiencies.

When a guided wave of a guide mode propagates in such a thin film structure, part of the guided wave energy is absorbed and converted to heat energy by the thin film. Part of the energy will generate a loss in the scattered light disturbance from the deficiences, thus weakening the light intensity of the guided wave along the direction of propagation. Generally, $I=I_0e^{-alphaz}$ indicates intensity variation of light intensity of the guided wave along the propagation direction z; alpha is the propagation attenuation coefficient of this guided wave. A concrete analysis is presented as follows:

1. Effect on propagation attenuation by absorption loss

Since there is absorption in the thin film, when the guided wave of a certain guide mode propagates in a thin film, thin film absorption attenuates the guided wave energy. The propagation constant $zeta_{zm}=beta_m-ibeta'_m$ of the guide mode can express this relationship well.

The guide mode equation of a thin film waveguide in the general form is [5]:

$$\zeta_{fm}d-\mathrm{tg}^{-1}\left[\eta_{cf}\frac{\zeta_{cm}}{\zeta_{fm}}\right]-\mathrm{tg}^{-1}\left[\eta_{sf}\frac{\zeta_{sm}}{\zeta_{fm}}\right]=m\pi\text{。} \qquad (2)$$

In the equation, $\zeta_{fm}=(k_0^2n_f^2-\zeta_{zm}^2)^{1/2}$; $\zeta_{cm}=(\zeta_{zm}^2-k_0^2n_c^2)^{1/2}$; $\zeta_{sm}=(\zeta_{zm}^2-k_0^2n_s^2)^{1/2}$; $k_0=2\pi/\lambda_0$, $\eta_{jf}=n_j^2/$ and $(n_f-ik_f)^2$ (TM mode) or $eta_{jf}=1$ (TE mode)

(j=c,s). Based on the structure of thin film waveguides, the numerical method is applied to solve this complex transcendental equation, thus obtaining the complex propagation constant $zeta_{zm}$ of various guide modes of this thin film. However, the virtual parts ($beta'_m$) of these propagation constants correspond to the propagation attenuation coefficients of the guide modes. Therefore, the propagation attenuation coefficient $alpha_a$ caused by the absorption loss is:

$$\alpha_a = 2\beta'_m \tag{3}$$

2. Effect on propagation attenuation of scattering loss

The effects on guide mode propagation by trace-rough boundary surfaces of thin film waveguides, and random fluctuation of refractive index in the thin film is manifested in the form of light scattering loss.

By using the Maxwell equations, we derive that the wave equation of a thin film waveguide medium (as shown in Fig. 1) is:

$$\left.\begin{aligned} &\nabla^2 \boldsymbol{E} + \mu_0\omega^2\varepsilon(x, z)\boldsymbol{E} = 0, \\ &\nabla^2 \boldsymbol{H} + \mu_0\omega^2\varepsilon(x, z)\boldsymbol{H} = \frac{\nabla\varepsilon(x, z)\times\nabla\times\boldsymbol{H}}{\varepsilon}, \end{aligned}\right\} \tag{4}$$

In the equation, epsilon(x,z) is the effective dielectric constant of the waveguide medium. For thin waveguides with micro-coarse boundary surface and fluctuation of refractive index, under the first-level approximation conditions, the effective dielectric constant is [6]:

$$\begin{gathered} \varepsilon(x, z) = \varepsilon^0(x) + \varepsilon^1(x, z), \\ \varepsilon^1(x, z) = \varepsilon_0 f_c(z)\{n_f^2\delta(x-0) - n_s^2\delta(x-0)\} + \varepsilon_0 f_s(z)\{n_s^2\delta(x+d) - n_f^2\delta(x+d)\} \end{gathered} \tag{5}$$

$$+2\varepsilon_0 \Delta n_f(z)\theta[0-x]\theta[x+d], \quad (6)$$

$$\varepsilon^0(x) = \varepsilon_0\{n_c^2\theta[x-0]+n_s^2\theta[d-x]+n_f^2\theta[0-x]\theta[x+d]\}, \quad (7)$$

In the equations, ϵ_0 and μ_0 represent, respectively, the dielectric constant and the magnetoconductivity in vacuo; delta(x) is the Dirac; theta[x] is the Heaviside function. It is shown that the waveguide deficiency can be indicated by equivalent additional dielectric constant $\epsilon^1(x,y)$ (additional source). These additional sources cause the scattering loss of guided wave propagation.

According to the optical theory of waveguides, a field of three modes of a thin film waveguide: air mode, base mode, and guide mode (the first two kinds are radiation modes) constitute a complete orthogonal base. Therefore in a waveguide, any field can be indicated by the linear combination of this orthogonal base [7]:

$$\left.\begin{aligned} E(x, y) &= \sum_{m=0}^{N} c_m(z)E_m(x, z) + \int g_r(z, \beta)E_r(x, z, \beta)d\beta, \\ H(x, z) &= \sum_{m=0}^{N} b_m(z)H_m(x, z) + \int v_r(z, \beta)H_r(x, z, \beta)d\beta_{\circ} \end{aligned}\right\} \quad (8)$$

In the equations E_m and H_m are the electric field and magnetic field of the various guide modes; E_r and H_r are the electric field and magnetic field of the radiation mode: $c_m(z)$, $b_m(z)$, $g_r(z, \beta)$, $v_r(z, \beta)$ are the to-be-determined radiation-value coefficients of the corresponding modes. The summations items in

the above equations are linear combinations of guide modes; the integration items are linear combinations of the radiation mode; this is the scattered optical field outside the waveguide; that is, the scattering loss. Therefore, to determine the scattering loss, the corresponding radiation-value coefficients g_r(z,beta) and v_r(z,beta) in the integration terms. By applying the orthogonal property of a mode in a waveguide [7], we have:

$$\left.\begin{aligned}\int_{-\infty}^{+\infty} E(\beta)E^*(\beta')dx &= \frac{\beta}{2\omega\mu_0}\,\delta(\beta-\beta'),\\ \int_{-\infty}^{+\infty} H(\beta)H^*(\beta')/n^2 dx &= \frac{\beta}{2\omega\varepsilon_0\mu_0}\,\delta(\beta-\beta'),\end{aligned}\right\} \tag{9}$$

In the equation, beta and beta' are the propagation constants of the mode. We can derive the radiation-value coefficient equations:

$$\left.\begin{aligned}&\frac{\partial^2 g_r(z,\ \beta)}{\partial z^2}-2i\beta\,\frac{\partial g_r(z,\ \beta)}{\partial z}=-\frac{\omega\beta}{2}\int_{-\infty}^{+\infty}\varepsilon^1(x,\ z)E_l(x,\ z)E_r^*(x,\ z,\ \beta)dx,\\ &\frac{\partial^2 v_r(z,\ \beta)}{\partial z^2}-2i\beta\,\frac{\partial v_r(z,\ \beta)}{\partial z}=-\frac{\omega\beta\mu_0}{2}\int_{-\infty}^{+\infty}\frac{\varepsilon^1(x,\ z)}{\varepsilon^0(x)}\,H_l(x,\ z)H_r^*(x,\ z,\beta)dx\\ &\qquad\qquad+\frac{\boldsymbol{e}_y\beta}{2\omega}\int_{-\infty}^{+\infty}H_r^*(x,\ z,\ \beta)\cdot\frac{\nabla\varepsilon^1(x,\ z)}{\varepsilon^0(x)}\\ &\qquad\qquad\times\nabla\times H_l(x,\ z)\boldsymbol{e}_y dx_\circ\end{aligned}\right\} \tag{10}$$

In the equations, it has been assumed that the fields of the initial guide mode are E_l(x,z) and H_l(x,z). The term with superscript * is the conjugate complex of the corresponding field; e_y is the unit vector along the y direction. From the solutions (g_r and v_r) in Eq. (10), when combined with the appropriate boundary conditions [8] of the deficiency section L of the thin film waveguide along the z direction, the scattering loss (DELTAI_d) of the waveguide can be derived. With further

derivation, the propagation attenuation α_d caused by this scattering loss is:

$$\alpha_d=\frac{\Delta I_d}{LI}=\frac{1}{L}\int_{-n_s k_0}^{n_s k_0}\langle|g_r^+(L,\beta)|^2\rangle\frac{|\beta|}{p}\,d\beta. \quad (11)$$

In the equation, $p=(n_s^2k_0^2-\beta^2)^{\frac{1}{2}}$. Here, the integration limits $n_s k_0$ and $-n_s k_0$ include two radiation modes. With respect to the TM mode, the v^+_r(L, beta) term should be used to replace g^+_r(L,beta) term in Eq. (11).

α_d includes the surface scattering loss α_s caused by micro-coarse boundary surface, and the bulk scattering loss α_v caused by the fluctuating refractive index. In the general situation, to a thin film system with absorption loss and scattering loss, the overall propagation attenuation of the guided wave should be

$$\alpha=\alpha_a+\alpha_d=\alpha_a+\alpha_s+\alpha_v \quad (12)$$

3. Analysis of Comprehensive Data

To quantitatively understand the propagation attenuation of a guide mode, in the article the properties of the propagation attenuation of a guide mode in thin films are numerically analyzed in three specific situations, with the results as shown in Figs. 2a, 2b, and 2c.

(a) The absorption loss α_0 is the major one;

(b) The surface scattering loss α_s caused by surface coarseness is the major one; and

(c) The bulk scattering loss α_c caused by fluctuating

refractive index of the thin film is the major one.

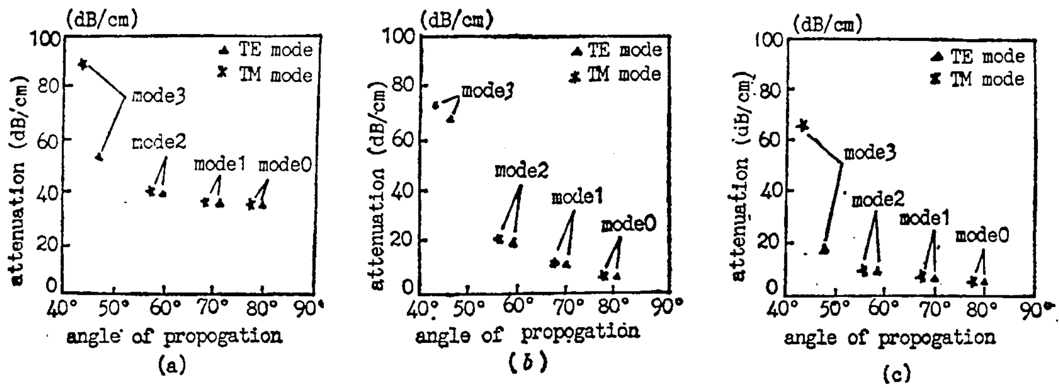

Fig. 2. Attenuation coefficients of guided modes for a thin film waveguide with the following structure: $n_o=1$, $n_f=2.2$, $n_s=1.5$, $nd=10\lambda/4(\lambda=632.8\text{nm})$ under the following conditions:

(a) $k_f=3.5\times10^{-5}$; $\sigma_c=\sigma_s=0.5$ nm; $\sigma_n=0.001$; $l_c=l_s=l_n=1\,\mu m$
(b) $k_f=3\times10^{-6}$; $\sigma_c=\sigma_s=3.5$ nm; $\sigma_n=0.001$; $l_c=l_s=l_n=1\,\mu m$
(c) $k_f=3\times10^{-6}$; $\sigma_c=\sigma_s=0.5$ nm; $\sigma_n=0.01$; $l_c=l_s=l_n=1\,\mu m$

By comparing the variation properties of attenuation in various deficiency situations with propagation angle theta of the guide mode, we can discover the following:

(1) Deficiency of a thin film is very sensitive to the propagation attenuation of a guide mode. The light extinction coefficient 10^{-5} and boundary surface coarseness of 2nm magnitude can be appreciably manifested in the propagation attenuation coefficient.

(2) Guide mode attenuation increases with mode level. When the absorption loss of the thin film is very small and can be neglected, the attenuation coefficients of the zero-level guide mode (TEO and TMO) are very small.

(3) In the situation of surface scattering and bulk scattering, the attenuation varies very rapidly with the propagation-angle variation At(theta). However, this variation is relatively moderate when the absorption loss is the major one. The function of scattering loss is very large to attenuation of a high-level guide mode. If the attenuation dependent on the propagation-angle variation At(theta) is extrapolated to theta=90^0, then At(theta) approaches a constant limit. Here, At(theta) is the variation type of propagation angle for the propagation attenuation coefficient alpha of various guide modes.

In the case of attenuation dependent on propagation-angle variation for the guide mode, the absorption and scattering losses in a thin film can be distinguished by propagation attenuation of different guide modes. Because in physics, when the At(90^0) value corresponds to infinity thickness of the thin film, the propagation attenuation is at the zero-level waveguide of the guide mode. In this case, therefore, At(90^0) does not have the effect of surface scattering loss, but is determined only by the light extinction coefficient k_f and the fluctuating

value of the refractive index in the thin film. For thin films of optical media prepared with conventional evaporation technique, the light extinction coefficient of the refractive index is approximately within the range 10^{-5} to 10^{-3}, correspondingly the propagation attenuation, when theta=90^0, the attenuation is approximately in the range between 10 and 1000dB/cm (with respect to the 632.8nm wavelength). However, when the fluctuating value sigma$_n$ of the refractive index varies between 0.001 and 0.^{0}1, the corresponding attenuations are between 0.0006 and 0.06 dB/cm. Therefore, for this particular propagation angle, when the light extinction coefficient $k_f > 10^{-6}$ for this thin film, the effect on attenuation due to bulk scattering is much smaller than absorption, so that the former can be neglected. Thus, by extrapolation the value of At(90^0) can be used to determine the light extinction coefficient k_f.

By using the light extinction coefficient k_f of the thin film, and according to the above-mentioned theoretical conclusion, we can determine the attenuation alpha$_a$ due to absorption for various guide modes. Then, by comparing alpha$_a$ and the measured propagation attenuation alpha$_m$ of the guide mode, the attenuation of various guide modes corresponding to scattering loss can be determined:

$$\alpha_d = \alpha_m - \alpha_a, \qquad (13)$$

Thus, the attenuation due to absorption loss and scattering loss of various guide modes can be distinguished.

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